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Life and Damage Monitoring-Using NDI Data Interpretation for Corrosion Damage and Remaining Life Assessments

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Introduction

The progress achieved in the understanding and modelling of fatigue and fracture in aircraft structures has led to the development of Damage Tolerance as the framework for ensuring continued airworthiness. Success of Damage Tolerance and Fail-Safe concepts combined with general economic conditions led to the current situation where an increasing number of aircraft are operated beyond their original design goal.

When today's ageing aircraft were designed and built most manufacturers made little allowance for corrosion. Corrosion protection was given low priority as the structures were typically not expected to remain in service beyond 20 years. While all elements of the aircraft industry (the operators and maintainers, certification authorities and manufacturers) recognised that corrosion could have a negative impact on the structural integrity, this impact could not be quantified until recently. Corrosion continued to be viewed as an economic burden since all corrosion found in an aircraft structure had to be "fixed". This maintenance practice usually included removal of the corrosion and when the net section was found to be reduced by a certain amount (typically 10%), the affected part had to be repaired. Often the term "fix" represented the replacement of an expensive component.

Research programs in the United States and Canada are developing a new corrosion management approach, based on that proposed by Kinzie and Peeler [1]. The Holistic Life Prediction Methodology (HLPM) being developed works within the existing aircraft structural integrity framework, and includes environmental as well as fatigue mechanisms for degradation. HLPM places new requirements on non-destructive inspections (NDI) for corrosion beyond simple material thinning. Quantitative measures of characteristic corrosion effects are required for structural analysis. The United States Air Force and the Canadian Department of National Defence are sponsoring work at (among others) the National Research Council Canada (NRC) to develop the data analysis tools and infrastructure to provide quantitative NDI results for HLPM in a maintenance environment.

Paper presented at the RTO AVT Specialists' Meeting on "Life Management Techniques for Ageing Air Vehicles", held in Manchester, United Kingdom, 8-11 October 2001, and published in RTO-MP-079(II).

Corrosion in Airframes

There are many types of corrosion that occur in aircraft structures (see Wallace and Hoeppner [2] for detailed definitions). This paper will concentrate on splice joints. The most common type of corrosion in splice joints is general attack on the faying surfaces. This can occur when adhesive bond or sealant between the layers breaks down, allowing moisture ingress. General attack is often accompanied by pitting corrosion. In severe cases, general attack evolves into exfoliation corrosion. Each of these types of corrosion can be characterized in terms of thickness loss of the original material. However, the effects of the different modes of corrosion on splice joint fatigue life are not well understood. Brooks et al.[3] have shown that the topography of the corroded faying surface can severely reduce fatigue life of a joint.

Another key mode of damage caused by corrosion in splice joints is pillowing. Pillowing is the deformation of the layers of the joint between the fasteners. This deformation is due to the fact that the corrosion products, aluminum oxides, have a much greater volume than the original material. The changes in the stress state of the splice joint due to pillowing change the locations, orientations, and aspect ratios of cracks emanating from the rivets [4], which are traditionally believed to be the life-limiting damage mode. Pillowing stresses may be large enough to be the cause of pillowing cracks, which are environmentally assisted cracks under sustained stress [5]. Wanhill [6] through very meticulous microscopic study has shown that nearly every fastener hole in a corroded splice joint may be subject to corrosion pillowing crack damage. He has in effect identified corrosion as a source of multi-site damage that might have significant implications to structural integrity.

Finally, the pillowing stresses can cause failure of the rivets themselves [7]. During disassembly of service-retired aircraft specimens at NRC, many examples of cracked and failed rivets have been found. Often, the failed rivets are still in place; held by corrosion, mechanical interference, or paint. This makes detection of these failed rivets by visual inspection impossible.

Pre-corroded (5% average thickness loss) splice joint coupon specimens have demonstrated close to 50% reduction in life to visible crack [8]. A holistic life prediction model including all identified corrosion effects in a splice joint at 10% average thickness loss has predicted over 80% reduction in life to critical crack size as compared to traditional analyses involving an 0.05" flaw growing to a 1 or 2-bay failure [9].

Nondestructive Inspection for Corrosion in Airframes: Current Practices

Despite years of increased funding for the development of nondestructive inspection (NDI) techniques for corrosion in airframes, little has changed in military or commercial aviation maintenance practices. In the commercial world, operators in general must repair corrosion damage upon discovery: the so-called "find and fix" practice. Thus NDI techniques sensitive to small amounts of corrosion damage are undesirable: operators feel current practices maintain an acceptable level of safety, and more sensitive NDI will end up increasing maintenance costs by provoking early repairs. Although military operators may not have the same regulatory requirements, the same conditions prevail.

In specific cases where flight safety is threatened by corrosion, such as the DC-9 spar cap or on landing gear, NDI techniques have been developed and successfully implemented in commercial operation. In other cases where imminent danger is deemed unlikely, such as splice joints and wing planks, NDI is in general restricted to visual inspection only. For commercial operators who achieve design service objectives in a much shorter time frame than military operators, this mode of operation has been somewhat successful from a safety point of view. Notable exceptions are the decompression accidents of a Boeing 737 operated by Far Eastern Air Transport in 1981, and another Boeing 737 operated by Aloha Airlines in 1988. Other incidents are documented in a report by Hoeppner et al. [10]. A key conclusion of this report was that the lack of consistent and stringent reporting requirements makes it difficult to determine when corrosion and/or fretting were important factors in the cause of incidents.

In the military environment, operation of ageing airframes beyond original design goals has in many cases come with increased maintenance costs and reduced availability due to corrosion. Detection of low levels of corrosion, even if below Structural Repair Manual (SRM) limits, provokes repair actions that may not have been planned. Thus sensitive NDI equipment and techniques are not welcome in the absence of supporting structural analysis tools.

The K/C-135 fleet operated by the United States Air Force (USAF) was previously targeted for full inspection of splice joints using the MAUS system. Recently it appears that the new NDI tools will not be implemented for this inspection, and visual inspection will continue to be used. Without any rigorous data to support the level of thickness loss detectable by visual means, this decision implies the operator is willing to accept a significant amount of section loss in these splice joints.

Holistic Life Prediction Methodology

Engineering is a profession based in science, but in the face of limited data or resources, the application of engineering judgement becomes an art. Life predictions of engineering designs are usually a compromise between what is practically achievable and scientifically rigorous. Years of progress in the physical sciences and rapid advances in information technology have opened new possibilities to engineers. Holistic life predictions, or in other words: "emphasizing the importance of the whole and the interdependence of its parts" [11] can now be considered.

Hoeppner has discussed the concepts of holistic life prediction methodologies as far back as 1971 [12]. At the time he and others searching for fundamental concepts had not yet used the word "holistic", however they had advocated the use of systems approach to structural integrity. Hoeppner used the terms "holistic lifing" and "holistic structural integrity based design" in his FAA workshop on Aircraft Structural Fatigue in 1979 which he first gave at the University of Toronto. At the time some of the focus of his work was on engine components [13]. In 1994 Hoeppner [14] presented an comparison between Safe Life, Damage Tolerance (as employed with starting "flaw" size specified) and Holistic Structural Integrity Design.

Some of the most fundamental aspects of HLPM, as it is referred to currently, that Hoeppner listed are:

- Design is "closed loop" and concepts of failure processes and "pathology" of structures pervade all phases of design and operation.
- The material is characterised as manufactured, considering intrinsic variability and process variability.
- HLPM considers fatigue as a multi-faceted process with extensive internal and external interactions in all stages of the process. (see Table 1).
- HLPM uses continuum mechanics but defines limits of applicability - is material and process specific.
- HLPM defines "defects" in relation to representation, variability, probability of detection (POD), and fitness for purpose. Introduces Discontinuity, Heterogeneity concepts.

- Surfaces are recognised as Discontinuity sources - thus they are characterised, modelled, evaluated, and controlled related to requirements and variability.
- Nondestructive inspection and destructive characterisation are pervasive throughout the design process. Probability of detection is intrinsic to activities. Inspectability is part of the design requirement.
- Variability in cyclic load response, variability in material behaviour, and variability in processes are intrinsic parts of design. Determinism is not used except for simplistic explanations.
- Probabilistic Life Estimation Techniques always are used. Fatigue, fracture, and related activities are recognised as intrinsic parts of the design process. Testing technology development is an ongoing activity.
- The load spectrum is recognised to be structure specific, and thus extensive effort is expended to develop standardised load sequences. Dwell effects are considered.
- Extensive effort is expended to understand the failure processes and methodology is developed for specific physically based degradation processes. Initiation concept used only to refer to start of a specific failure process. Physical characterisation of the degradation process is pervasive throughout, with control of material and process related to the specific failure mechanism. Inspection is pervasive throughout related to the specific degradation/failure process.

Table 1. Stages in fatigue life (after Hoeppner[14]). Total life L=L1+L2+L3+L4.

L1	L2	L3	L4
NUCLEATION	"SMALL CRACK" GROWTH	STRESS DOMINATED CRACK GROWTH	FAILURE (FRACTURE)
Material failure mechanism with appropriate stress/strain life data Nucleated discontinuity (not inherent) type, size, location Presence of malignant D*, H* Possibility of extraneous effects: • Corrosion • Fretting • Creep • Mechanical Damage	Crack Prop. Threshold related to structure (micro) Structure dominated crack growth Mechanisms, rate Onset of stress dominated crack growth Effects of: • R ratio • Stress state • Environment (t, chemical, T) • Spectrum ⇒ waveform	Fracture mechanics: • similitude • boundary condition (LEFM – EPFM?) Data base** Appropriate stress intensity factor Initial D*, H* size, location, type Effects of: • R ratio • Stress state • Environment (t, chemical, T) • Spectrum ⇒ waveform	K_{Ic} etc. C.O.D. Tensile/compressive buckling

*Discontinuity, Heterogeneity, **i.e. Mil. Handbook 5

- Probabilities of occurrence of specific corrosion, wear, fretting, and thermal degradation mechanisms acting singly or conjointly with fatigue are acknowledged as part of the failure process. Constant evaluation, model development, test method development, and design methodology development are intrinsic to design process.
- Attempts to characterise details of the failure process. ACTIONS based on understanding and recognition (of knowledge gaps) of failure PROCESSES.
- Recognises probability of localised discontinuity formation in relation to failure processes. Recognises high probability of multiple discontinuity sites (e.g. fatigue cracks, corrosion pits, etc.) Recognises need for assessment of Principal Structural Elements, Structurally Significant Items, and Structurally Significant Locations on the basis of failure process interaction effects. Defines "damage" growth in trackable inspection parameters or recognises need to limit lives of components.
- Microstructural control through process control always used to control and optimise response of materials for specific failure mechanisms.
- Design is viewed in terms of response brought about by extrinsic factors. Develops response parameters. Approach is holistic.
- All life assurance personnel are trained in failure processes and structural pathology. A proactive methodology to provide immediate feedback into the design system of "lessons learned" is a part of the design system.

In 1998 Brooks et al.[3] have shown that the HLPM can be embodied in a practical analytical process that can account for corrosion fatigue effects on aircraft structural integrity. At the same time Simpson and Brooks [15,16] proposed the integration of corrosion into the aircraft structural integrity program (ASIP) using USAF ASIP tasks to illustrate how a revised program would be structured. While in the light of the conservatism of many in the structural integrity community the concept they have proposed might seem revolutionary, the changes can be introduced selectively.

Brooks and co-workers, partly under the support of USAF Corrosion Maintenance Initiative program, have developed a computer code ECLIPSE [17] - Environmental and Cyclic Life Interaction Prediction Software. ECLIPSE is based on HLPM, and the software has been exercised extensively on specific lap splice joint geometries and on early-pitting-to-fracture specimens and components. The software is being modified so that it can assist in making holistic life predictions for other geometries that may or may not have different driving mechanisms for the discontinuity progressions. ECLIPSE is expected to evolve to incorporate all fundamental aspects of HLPM listed above. It is currently subject to an intense verification effort under the USAF Corrosion Fatigue Structural Demonstration (CFSD) program, which also has been tasked with development of some of the data needed for HLPM. Phase 2 of the CFSD is currently in progress[18].

While models of discontinuity state evolution are fundamental to HLPM (ECLIPSE), practical application of the methodology to account for corrosion fatigue degradation requires the knowledge of corrosion growth rates in response to known environmental spectra and quantified nondestructive assessment of current ('as-is') condition. Significant progress in the field of corrosion rate assessment has been published by Kinzie [19]. The progress in the quantification of 'as-is' state is described in the following section.

NDI in Support of the HLPM

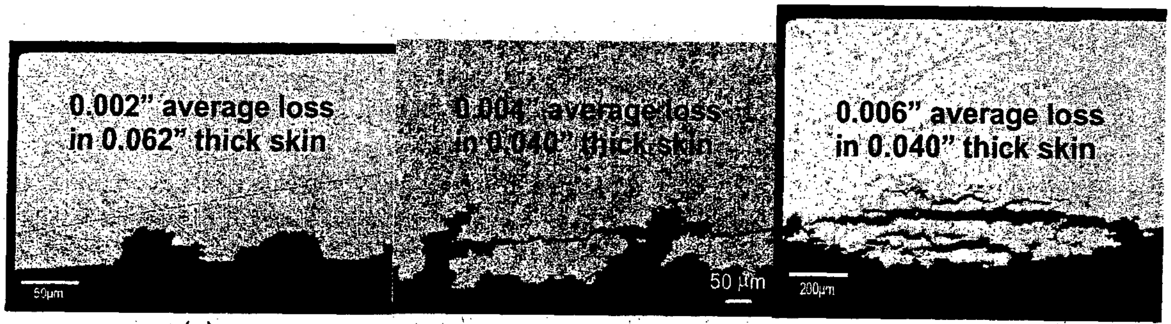
The first applications of HLPM were directed at the fuselage splice joint. This is a common element of construction for transport aircraft, including large ageing fleets such as the K/C-135, C-141, C-130, B-52, and P3/CP-140 fleets operated in the U.S.A. and Canada. Although there are many different joint configurations used, there are common properties which make NDI development applicable across a broad range of applications. The splice joint was also the target of many NDI development programs sponsored by the Federal Aviation Administration (FAA) in the USA in the early 1990's, thus there are a number of nearly mature NDI techniques available for this application.

HLPM is not only concerned with corrosion but also fatigue including MSD. Since fatigue has been the focus of intense study and concern in aircraft structural integrity, NDI methods used for crack detection are considered mature. There is a concern, however, that corrosion and modifications (repairs) to ageing structures will result in cracks in inaccessible surfaces and deeper layers which are less amenable to inspection. Repairs where flush rivets are replaced with button head rivets, or bonded or fastened doublers are installed, are examples of situations where crack detection is adversely affected. For the integration of NDI with maintenance and analysis tools, better recording of NDI for cracks is also a concern. Even data from manual inspections can be entered in databases, with a resulting improvement in damage reporting, tracking, and integration with analysis tools.

Previous NDI for corrosion in splice joints was aimed at measuring "general" thickness loss, that is, a spatially averaged measure of thickness of the individual layers of the joint. These developments were aimed at satisfying current FAA and industry practices. The analysis models developed to support HLPM require this measure or metric of corrosion, but also require information about faying surface topography and, in riveted joints, pillowing deformation and cracking.

Many NDI techniques have been developed to determine "general" thickness loss. Thickness measurement of the first layer can be carried out using ultrasonic, thermographic, or single frequency eddy current techniques. There are some difficulties in inferring general thickness loss from thickness measurements: First, sheet tolerances in the as-manufactured state are in the order of 5% for common skin thicknesses. Second, in older aircraft, variations in manufacturing and repairs are much more common, and often poorly documented. Second and third layer thickness measurements are much more difficult, and it is widely believed that multi-frequency and pulsed eddy current techniques hold the most promise for practical use in this situation.

For the determination of faying surface topography, it has been shown by Smith and Bruce [20] that the topography of the top faying surface can be measured using ultrasonic methods. However, the interlayer gap in corroded specimens is poorly defined, often without mechanical bonding, and containing varying amounts of corrosion product. Thus information about the second and deeper layers is almost impossible to obtain directly. It is believed that faying surface topography can be correlated with general thickness loss, and experimental work to date supports this [21,22] (see Figure 1 and Figure 2). This means that many of the currently available NDI techniques can be used for this metric.



(a) (b) (c)

Figure 1. Changing faying surface topography with thickness loss in sections from service-retired aircraft splice joints (from Bellinger et al. [22]).

NDI techniques also exist for measuring pillowing deformation, ranging from simple mechanical devices to automated optically-based systems [23]. The combination of a general thickness measurement indicating less than nominal thickness with an indication of pillowing is often the best indicator of the existence of material loss due to corrosion.

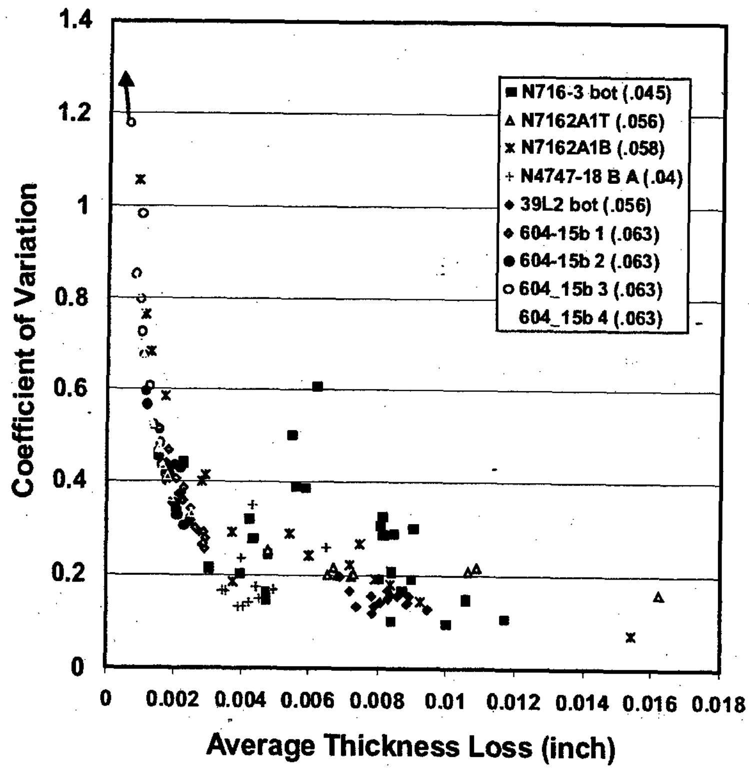


Figure 2. Correlation of faying surface topography feature with amount of material loss (from Bellinger et al. [22]).

NDI Infrastructure Requirements in Support of HLPM

In order to achieve better NDI, and make better use of NDI in performing a structural integrity assessment, there are "infrastructure" issues which need to be addressed. A conceptual approach to depot maintenance for corrosion in airframe components is shown in Figure 3. Inspection planning and recording become a significant task when faced with the large areas of splice joints on transport aircraft. Analysis of data also needs to be improved and automated so that quantitative NDI results on the metrics of interest can be directly entered into the structural analysis tools. NDI for fatigue cracks will likely have to undergo the same application of more rigorous data recording and analysis in order to achieve accurate assessment of MSD/WFD scenarios in the presence of corrosion.

The USAF is sponsoring the Corrosion Quantification (CQ) program at S&K Technologies, the Institute for Aerospace Research of NRC, and LMI Automotive in an effort to address these concerns. An existing proprietary inspection planning tool is being enhanced to allow for any type of NDI system and for the input of wireframe diagrams of airframes for data registration purposes (see Figure 4 for an example). The inspection planning software is also being enhanced to allow for integration with existing maintenance databases. Existing and new data registration and fusion tools are being evaluated for their ability to generate reliable and quantitative data from NDI, and for the export of this data directly into structural analysis tools.

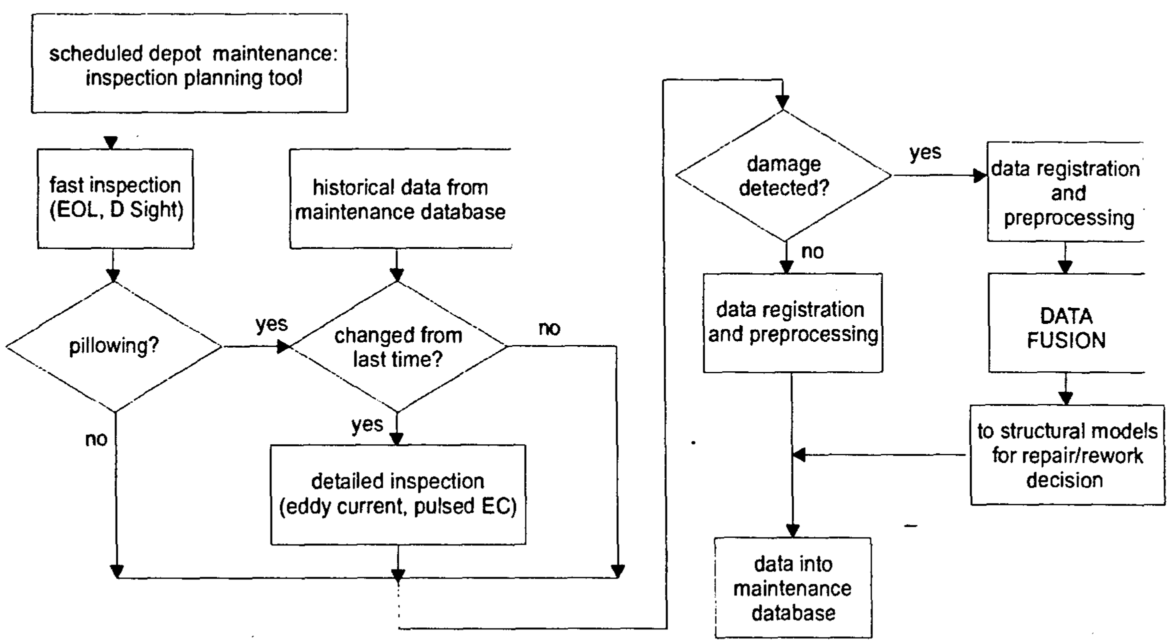


Figure 3. A conceptual flowchart for splice joint corrosion NDI during depot maintenance.

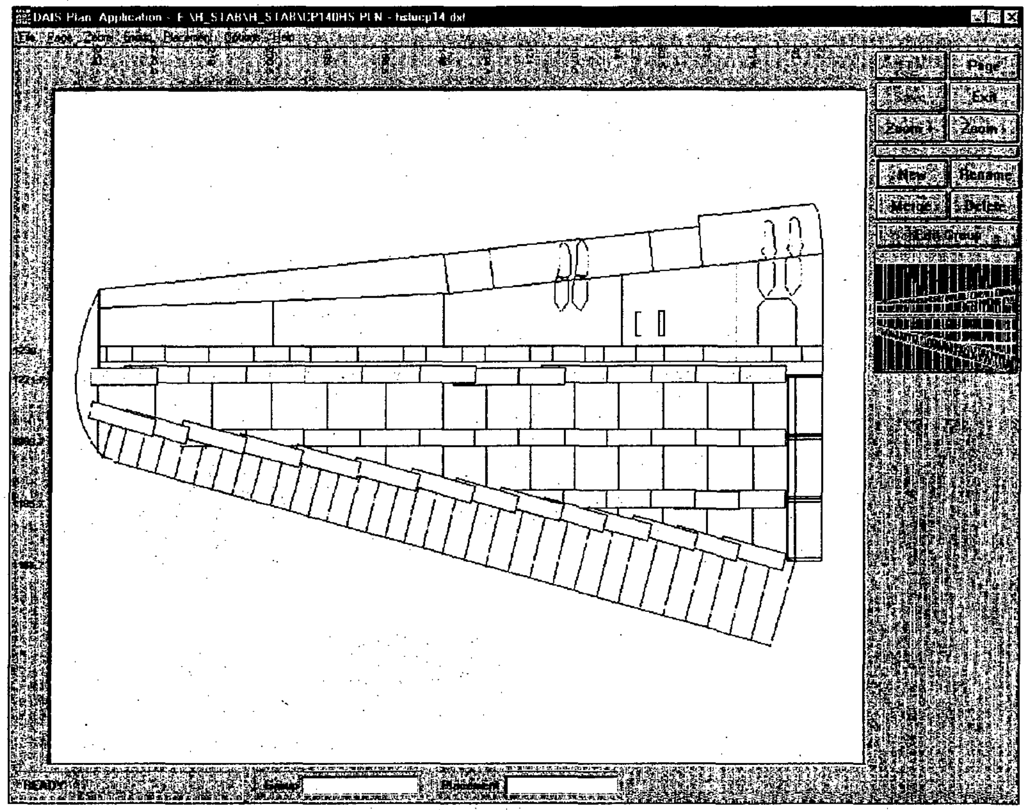


Figure 4. A view of inspection planning software being enhanced under the CQ program.

An example of data fusion applied to NDI of a lap splice joint from a retired Boeing 727 aircraft is shown in Figure 5 (see reference [24] for details). The data shown is for the second layer thickness. The image on the top shows thickness loss from nominal, obtained from the fusion of pulsed eddy current and Edge of Light inspections. This data has been registered on a co-ordinate system, and then can be compared to the image on the bottom, which is a thickness map obtained after disassembly of the joint. While these are preliminary results, they show promise for the use of modern data analysis in obtaining quantitative results from NDI. The CQ program is building on these results and seeking further improvements.

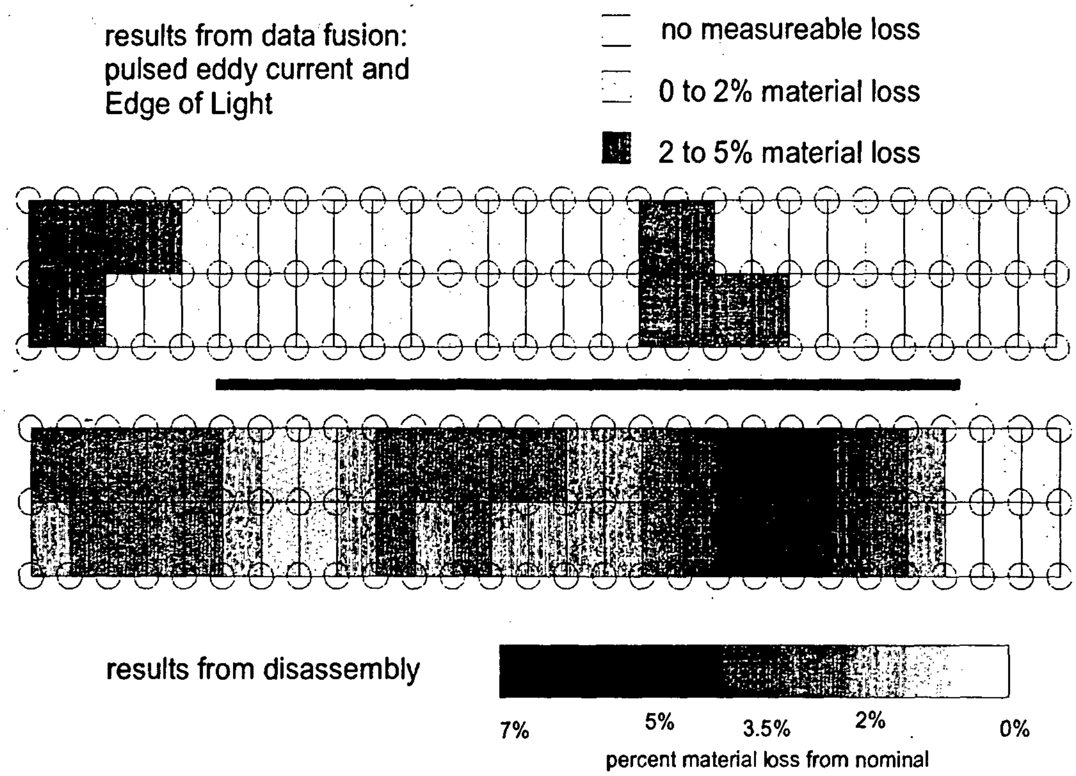


Figure 5. An example of data fusion used to obtain thickness data for the second layer of an actual lap splice joint (from Forsyth and Komorowski [24]).

Integration of HLPM Into the Maintenance Environment

A typical maintenance cycle time-line is shown in Figure 6. Between the end of the previous planned depot maintenance cycle, and the entry of the aircraft into the next PDM, no focused corrosion inspections are carried out. There are two reasons for this:

- Corrosion NDI tools are not deployed, and unless corrosion damage becomes severe enough to be evident under visual inspection, no corrective action is undertaken.
- In the absence of tools which account for the structural impact of corrosion, focused inspections before entry into PDM are discouraged as no rationale for a decision to continue to operate an aircraft with known corrosion damage can be found.

Aircraft thus enter PDM in an unknown condition, and the extent of damage and thus time required to repair (fix) corrosion can not be predicted, spares can not be ordered, special repairs can not be designed etc.

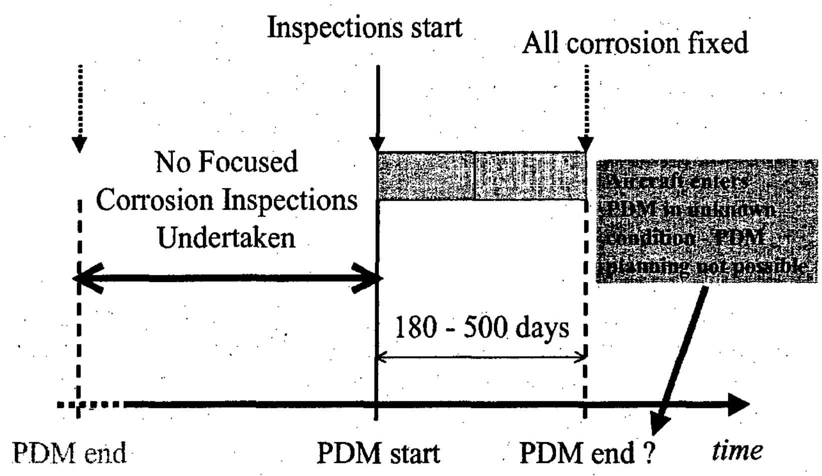


Figure 6. Current aircraft maintenance cycle time-line. PDM – planned depot maintenance.

The application of HLPM to splice joints has reached the maturity level that, along with the NDI tools described above, allows fleet managers to consider transitioning the technology. This process should occur gradually such that the necessary infrastructure can be put in-place along with staff training. Recent completion of the USAF Corrosion Maintenance Initiative (CMI) program and availability of dedicated corrosion splice joint inspection equipment allow some changes to be introduced today towards a more planned approach to PDM, as shown in Figure 7.

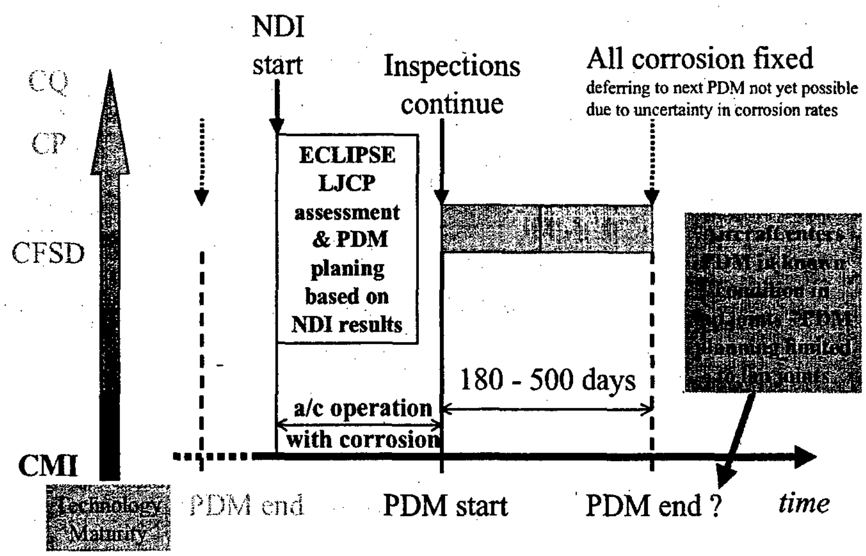


Figure 7. First step in the introduction of HLPM and NDI to Predict and Manage approach to aircraft maintenance. CFSD, CP and CQ are USAF corrosion technologies programs. LJCP – lap joint corrosion prediction program.

NDI inspections for corrosion could be carried out several months before an aircraft's entry into the PDM. Inspection data processed using the tools developed so far will help plan corrosion repairs, as the extent of damage would be known. Since ECLIPSE performs calculations from 'as-is' to 'to-be', the safety of operation of the aircraft with known corrosion would be assured. It is possible that some damage identified will require immediate attention. However, this is unlikely as such findings would indicate that current practices (as shown in Figure 6) are unsafe.

The benefits of the introduction of HLPM based code like ECLIPSE and NDI into the aircraft maintenance cycle will have to be limited to splice joints until the completion of CP – corrosion prevention and CQ – corrosion quantification programs which aim to expand the HLPM (ECLIPSE) to other aircraft structures. More data is also required to gain confidence in the ability to predict the rates of corrosion damage accumulation. Figure 8 shows the PDM cycle time line with fully implemented mature HLPM and NDI technologies. The PDM cycle will be significantly shortened, as few surprises will be uncovered in maintenance.

It is also possible that aircraft slated for near-term retirement will not require all corrosion to be fixed, or that less difficult repair schemes such as the application of corrosion prevention compounds (CPC) could be used instead of grindouts or part replacement. Data supporting confidence in corrosion growth rates and the efficacy of CPC's is being obtained to support this. Aircraft structures will be safely operated with known levels of corrosion until they are either retired or repaired at most opportune time.

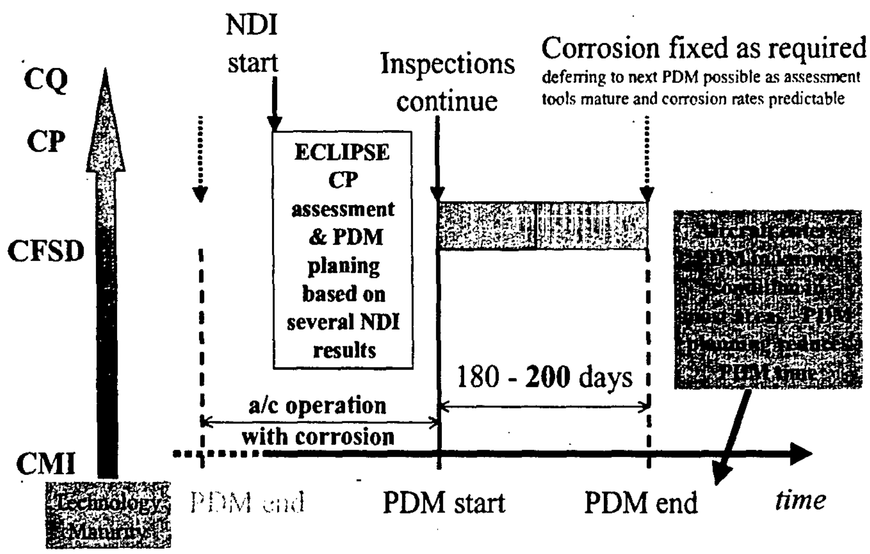


Figure 8. Full implementation of Predict and Manage HLPM based aircraft maintenance.

Conclusions

Holistic life prediction methodologies have been under development for at least the last 30 years. The ever-increasing availability of cheap computing power has now allowed HLPM to be implemented in practical analytical procedures. In the case of aircraft splice joints, the NDI technology required to implement HLPM is available today. The benefits of the implementation of HLPM into fleet management are immediate with current capabilities, and will increase as existing research programs come to fruition.

Acknowledgements

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